

AMENDMENTSIn the Specification:

Please amend paragraphs [0003], [0011], [0026], [0074], [0075], [0078], [0079], [0085], [0086], [0089], and [0094] as follows:

**[0003]** New micro-machining techniques ~~are~~ required to meet the growing demand for miniaturized products and processes. Abrasive waterjets have the potential to develop into an important micro-machining technique, but before this can happen new technologies are needed to generate and to control the flow of pressurised water flows carrying abrasive particles.

**[0011]** The pressure differential imposed across settled beds of abrasive particles, with mean particle diameters greater than about 100 µm, causes water to percolate through the bed. Therefore, the mixture flowing out of the bed has a higher water content than is present in the bulk of the bed. Abrasive waterjets operating with settled beds of abrasive particles have relied on this water percolation for the bed to form and to aid in the flow of abrasive particles out of the beds. However, water percolation practically ceases with abrasive particle sizes needed for micro abrasive waterjets and this affects not only how beds can be formed, but also the time dependent ~~Theological~~ rheological properties of abrasive beds and the structure of the beds during operation of abrasive waterjet apparatus.

**[0026]** However, such valves have limitations as regards apparatus to generate micro abrasive waterjets because:

- a) Valve elements and seats cannot be easily fabricated from ultra hard materials to withstand wear if the valves are to be closed or opened under the high pressures in abrasive waterjet cutting apparatus;
- b) The small size of the valve elements needed for micro abrasive ~~waterjet~~ waterjet apparatus makes it impractical to provide robust drive

mechanisms that penetrate through pressure containments to actuate valve elements;

- c) Sealing of valve element drive mechanisms, where they do pass through the pressure containment, is very difficult in the presence of the fine abrasive particles used in micro abrasive waterjet cutting; and
- d) The valves have flow passages that contain spaces where abrasive particles can accumulate and subsequently be released, when the sudden release of accumulated abrasive can cause cutting nozzles on abrasive waterjet apparatus to block.

**[0074]** Pressurised water from a pump 25 enters the apparatus through conduit 1. When valve 5 is open, a major proportion of the water passes through conduit 4 and valve 5 and thence, via conduit 7, to a junction 6, where it recombines with a small proportion of the water flow which has passed through conduit 2 and a first restrictor 3. Of the total flow from the pump 25, about ninety percent flows from junction 6, through a second restrictor 10 and conduit 11, which is provided with a non-return valve 26, to junction 14, bypassing an abrasive storage vessel 19. The remaining ten percent or so of the water flows through the buffer volume 24 and conduit 9 to the storage vessel 19, where it displaces abrasive particles and water out of the bottom of the storage vessel 19 through conduit ~~1-S 18~~, an abrasive flow restrictor 17 and conduit 20 to junction 14. At junction 14, the flow from the storage vessel 19 joins the ninety percent or so

**[0075]** of the flow that bypassed the storage vessel 19. From junction 14 the water and abrasive particles pass through conduit 15, which is provided with a shut-off valve 27, to a cutting nozzle 16, where the pressure energy of the fluid is converted to velocity energy to form an abrasive fluid jet jet 23. The percentage of water that flows to the top of the abrasive storage vessel 19 depends mainly on the cross-sectional areas of the restrictors 10 and 17 and conditions within the abrasive bed in the abrasive storage vessel 19.

[0078] The buffer volume 24 prevents abrasive particles carried out of the abrasive storage vessel 19 during depressurization of the apparatus from reaching the vent valve 21. The clean water flow to the top of the abrasive storage vessel 19 during pressurization of the vessel and during normal cutting operations flushes abrasive particles back from the buffer volume 24 into the abrasive storage vessel 19.

[0079] The non-return valve 26 provided in conduit 11 prevents abrasive particles from the

[0085] Figure 3 shows a flow circuit for operating an apparatus in which the abrasive storage vessel 19 contains a suspension of abrasive particles at the same abrasive/water weight ratio as is required at the nozzle 16. In the circuit shown in Figure 3, the non return valve 29 is spring loaded to give a pressure drop greater than the pressure ripple from pump 25. When valve 28 is open all the water entering conduit 1 flows to period of decaying water pressure, the abrasive concentration at the nozzle 16 is higher than the steady state cutting concentration. This higher abrasive concentration is beneficial in enabling a jet to make an initial penetration into the material being cut.

[0086] The operation of the flow circuit shown in Figure 1, using a jet pump arrangement, begins to break down as nozzle diameters are reduced to the point where laminar flow occurs in parts of the circuit. It is then more appropriate to use the flow circuit of Figure 2 which shows the circuit for a basic abrasive waterjet apparatus. A limitation of the circuit shown is its inability to stop abrasive discharge controllably. Any drop in delivery pressure from the pump 25 with valve 5 closed causes flow out of the bottom of the abrasive storage vessel 19. This flow has a high concentration of abrasive, which can settle out and block conduit 15 and nozzle 16. Hence it is preferred to use the circuit with a control strategy that increases the pump delivery pressure when valve 5 is closed. With increasing pump delivery pressure water flows back up conduit 18 into the base of the abrasive storage vessel 19, stopping the flow of abrasive to the nozzle 16. The nozzle 16 can then be moved rapidly from the end of a completed cut to the start of a new cut.

~~with only water discharging, or if a shutoff valve 27 is fitted, the shut off valve 27 can be safely closed with only water passing therethrough.~~

[0089] Abrasive concentrations in the abrasive storage vessel 19 can be varied from about seventy percent by weight of abrasive in water, down to less than ten percent. By adjusting the sizes of the restrictors 3, 10, 17 in the circuits shown in Figures 1 and 2, a wide range of abrasive to water ratios can be achieved at the nozzle 16 for a given ratio present in the abrasive storage vessel 19 and a specific rheological condition of the mixture. The maximum abrasive concentration that can be passed through the nozzle 16 depends on the abrasive particle size. With particle diameters less than a tenth of the nozzle diameter, abrasive concentrations up to fifty percent by weight can be made to flow through the nozzle 16, although cutting performance tends to be poor with such high abrasive concentrations. Concentrations of the order of ten percent by weight of abrasive provide a good compromise between cutting speed and efficient use of abrasive. When cutting speed is the main consideration the abrasive concentration can be increased to 20 to 30 percent.

Figure 4 shows a form of valve suitable for closing off conduits carrying high pressure fluids and in particular fluids transporting abrasive particles. Different forms of the valve can be used-as valve 5 of Figures 1 and 2; as valve 21 of Figures 1 to 3; as valve 28 of figure 3; as valve 141 of Figures 1 to 3; and most importantly as valve 27.

With the valve open, fluid enters through an inlet connection 80, and passes through a tube 78, and a pair of valve seats 75 and 74, to an outlet connection 81. Apertures are provided in each valve seat 74, 75 which are aligned in an open position of the valve, allowing fluid to pass therethrough. To shut off the fluid flow, a first valve seat 75 is slid over a second valve seat 74 to a position in which the aperture through the first seat 75 is sealed off by a face of the second seat 74. The seats 74 and 75 are made of an ultra hard, low friction material, such as polycrystalline or chemical vapor deposition diamond that has a flat polished surface. A spring 77, acting on a carrier 76 for the first seat 75, loads the seats 74,

75 together. When the fluid in the inlet connection 80 is pressurised, the major load on the seats 74, 75 can be due to fluid pressure acting on the upper end of the tube 78. The tube 78 is supported by a seal assembly 79 mounted to a valve body 70, and is guided in a slide 71. The tube 78 maintains connection to the first valve seat 75, denying dead space, and acts as a strut under buckling. Its unsupported length is a compromise between the need to contain the system pressure, to avoid buckling and to avoid applying excessive side loads that could result in tipping of the first seat 75 relative to the second seat 74.

The diameter of tube 78 in the area of the seal assembly 79 can be increased or decreased to change the axial loading on the tube by pressure in the inlet connection 80.

In the embodiment shown in Figure 4 two pneumatic cylinders 72, mounted to the valve body 70, carry the slide 71, which is provided with a plurality of seals 73, and effectively forms the piston for both of the pneumatic cylinders 72. Application of compressed air at ports 83 and 84 thus opens and closes the valve. Movement of the slide 71 could also be produced by other forms of actuation. The movement range of the slide 71 is limited by stops 82 provided on the body 70 and on the slide 71. The inlet connection 80 may be offset laterally from the outlet connection 81 by half the permitted movement range of the slide 71. The tendency for buckling of tube 78 may thereby be minimised.

[0094] The arrangement shown allows one central physical connection to be used in place of the two physical connections used in the arrangement disclosed in the above International Patent Application. With only central physical connection cartridge assemblies are far easier to fit into the base 50 and no misalignment of connections is possible. The removal of cartridges from the base 50 can be aided by applying compressed air through conduit 56 once the barrel 51 is undone. Plug 57 in the barrel 51 provides a small annular gap between the plug and barrel, through which air can pass when the barrel is slid over the cartridge. The annular gap between plug 57 and the barrel 51 is sufficiently small that the cartridge 41 is not extruded into the gap when the apparatus is pressurised.

For apparatus with nozzle diameters less than about 20 µm the risks of contamination of the abrasive and parts of the apparatus subject to water flow require that preparation of the abrasive and filling of abrasive storage vessels is carried out under clean room conditions. Assemblies that include the abrasive storage vessel 19, isolation valve 27, nozzle 16 and internal passageways can be removed and fitted onto multi axis motion systems as a single unit. Installation of the assembly can be arranged so that connections to conduits 9 and 11 of Figures 1 to 3 are automatically made, along with connections to power the actuator on valve 27.

Referring to Figure 6, fluid entering from conduit 11 and abrasive and water flowing out of the abrasive storage vessel 19 through restrictor 17 enter tube 78 just below restrictor 17 to form a suspension therein. The suspension passes down tube 78, through seats 74 and 75 into tube 85 that abuts against nozzle 16. The flow passages from entry to tube 78 to the nozzle 16 are free of any cavities or spaces where abrasive can accumulate. Tube 85 is sealed by seal assembly 79 and can be loaded against nozzle 16 by means of spring 77 and fluid pressure loading on the seats 74 and 75. The operation of the valve in Figure 6 is generally as described in reference to the valve in Figure 4.

Wear on the seats 74 and 75 occurs very locally in the areas of the seat faces and bores where the initial opening and final closing flows are concentrated. The seats 74 and 75 and their carriers 76 can be rotated in small increments from time to time so that erosive wear is evenly spread.